Pre-Impact Damage Assessment Using X-ray Tomography of SiC Tile Encapsulated In Discontinuously Reinforced Aluminum Metal Matrix Composite.

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Abstract : Encapsulation of monolithic ceramic materials is one concept for confinement of candidate armor ceramic materials which enables both constraint during ballistic impact and retention of damage fragments for post-impact evaluation by either destructive or non-destructive methods. Non-destructive examination is essential for the pre-impact baseline characterization of consolidated samples, which subsequently will be tested ballistically and then further characterized for damage in the post-impacted condition. Such non-destructive characterization of experimental samples of SiC ceramic tile material encapsulated within discontinuously reinforced aluminum metal matrix composite, DRA, was conducted using x-ray computed tomography, CT. Each sample consisted of one 10 cm x 10 cm x 1.2 cm thick SiC ceramic tile encapsulated with 356/SiC/60p-F DRA forming a test sample of 15.2 cm x 15.2 cm x 9 cm thick overall dimensions. Both digital x-ray radiography and computed tomography were performed on the samples using a custom built ACTIS 600/420 x-ray computed tomography scanner from Bio-Imaging Research, Inc., to characterize and document the "as fabricated" samples prior to planned ballistic testing.

Results of three samples fabricated by the pressure infiltration casting process indicated pre-existing voids in the MMC encapsulant material and substantial multiple cracks in both the MMC and the SiC materials. Such defects in the as-fabricated samples, had they gone undetected, would have been difficult to separate from later anticipated ballistically-induced damage. Also, significant displacement of the SiC tile was detected indicating an undesired repositioning of the SiC tile during the encapsulation casting step. A subsequent sample fabricated by the presssureless metal infiltration process appears more promising as conventional x-rays reveal the absence of the extensive cracking observed in the previous samples. This report discusses the application of x-ray computed tomography (CT) to pre-impact characterization of encapsulated ceramic target materials.

Keywords: Damage Assessment, X-ray Tomography, SiC, DRA MMC, pressure infiltration, pressureless infiltration

1. INTRODUCTION

Both pre-impact and post-impact characterization is necessary for understanding the damage cracking modes in ballistically tested encapsulated samples. Without pre-impact characterization no sample initial state baseline can be established. Damage pre-existing in the initial state, consisting of voids, inclusions, cracks, or other defects, may significantly affect ballistic test results and their interpretation and thus, should be accounted for in subsequent ballistic and damage analysis. Different non-destructive testing techniques, including x-ray radiography testing and ultrasonic testing, have been used in the past to assess internal structure in a variety of materials. However, these techniques have limitations that make obtaining detailed volumetric (i.e., three-dimensional) data extremely difficult, if not impossible. Characterization of opaque ceramic materials is also required to provide both quality assurance control and damage assessment of candidate armor ceramics in either confined or applique configurations. Destructive characterization techniques have the limitation of statistical sampling of selected items, which are then no longer functional for further ballistic testing or in service use. Non-destructive techniques avoid that limitation but vary in their capability to detect and record the presence, location, orientation, shape and size of multiple flaw and damage types of interest in such applications, particularly where more than one type of material is involved.

Ceramics are strong in compression, stiff, hard, and brittle. These attributes can be exploited to resist, if not defeat, ballistic projectiles. Unconstrained ceramic materials are less than fully effective in resisting ballistic impact. Fully constrained ceramics have been demonstrated to be more mass efficient in resisting and, in some cases, defeating certain ballistic projectiles (Hauver) [1]. Encapsulation of ceramic tiles in monolithic Ti-6Al-4V metal alloy by electron beam welding and subsequent hot isostatic pressing, (HIP), has been investigated by (Bruchey and Horwath et al.) [2]. Encapsulation of armor ceramics by cast aluminum metal matrix composites, AL MMCs, is being considered to take advantage of the intrinsic higher specific modulus of the MMC material and the potentially lower cost casting fabrication method. Earlier efforts utilizing non-destructive ultrasonic techniques for inspecting discontinuously reinforced aluminum DRA materials did not produce suitable results (Sincebaugh) [3].

Recovery of impacted armor ceramics is necessary to examine the microstructural and fractographic features of the damaged target material. Target systems using unconfined ceramic elements are normally incompatible with recovery of the impacted ceramic fragments. Encapsulated ceramics have more inherent post-

impact recoverability as long as the encapsulant remains substantially intact. Also, an encapsulant with substantial stiffness may play a significant role by preventing or minimizing bending in the ceramic rear face during ballistic impact. Reduction in rear face bending of the brittle ceramic avoids high tensile bending stresses, which can induce premature back surface crack initiation and decrease ballistic performance.

1.1 Non-destructive Testing & X-ray Computed Tomography

X-ray and various ultrasonic inspection techniques have been used to detect internal defects that do not intersect the external surfaces. However, conventional x-ray radiography suffers from the absence of three-dimensional (3D) information, since a film radiograph or fluoroscopic image is a shadowgraph. Ultrasonic inspection techniques can suffer from signal dispersion in ballistically tested materials with extensive cracking or fracture damage. This makes it difficult to produce an accurate two-dimensional (2D), much less a 3D, ultrasonic image of the damage. X-ray computed tomography is broadly applicable to any material or test object through which a beam of penetrating radiation may be passed and detected, including metals, plastics, ceramics, metallic/nonmetallic composite material, and assemblies. The principal advantage of CT is that it provides densitometric (that is, radiological density and geometry) images of thin cross sections through an object. Because of the absence of structural superposition, images are much easier to interpret than conventional radiological images. The user can quickly learn to read CT data because images correspond more closely to the way the human mind visualizes 3D structures than projection radiography; that is, film radiography, real-time radiography, and digital radiography [4,5].

1.2 Three-Dimensional Visualization of Multiple CT Scans

The excellent dimensional accuracy and the digital nature of CT images allow the accurate volume reconstruction of multiple adjacent slices. The slices are "stacked" to provide 3D information through out the entire object or a section of the object. Two ways of visualizing volumetric data are multiplanar reconstruction (MPR) and 3D reconstruction. Multiplanar reconstruction (visualization) displays top, front, side, and oblique slices through the object. The orientation of the top slice is parallel to the cross-sectional image plane. The front slice is orthogonal to the top slice. The side slice is orthogonal to both the top and front slices. The oblique slice can be placed on any one of the other three slices. The MPR display is similar to an engineering drawing. However, each view (i.e., top, front, side, and oblique) is a slice with finite thickness through the object, not a 2D projection. The top, front, and side slices can be moved anywhere in the reconstructed volume. The oblique slice can be rotated through 360 degrees. Dimensional analysis, image processing, and automated flaw detection and measurement can be performed with MPR images.

Volumetric data is displayed as a 3D solid object in 3D reconstruction (visualization), and the orientation of the solid in space can be changed to facilitate different views. The solid can also be "virtually" sectioned by only displaying part of the reconstructed volume, which creates a "virtual" cutting plane on the solid showing the x-ray density values on that plane. This plane may be orthogonal to the cross-sectional image plane. In effect, virtual sectioning shows the cutting plane as it would look if the object was actually destructively sectioned along that plane. Green and Wells [6] have previously demonstrated the use of CT scans with impact ceramics and composites target materials.

2. Technical Approach

2.1 Sample Design

The samples used in this study were sized the same as those used by Horwath & Bruchey [2} for their EBW/HIP Titanium Ti-6Al-4Valloy encapsulated samples. A schematic of the sample dimensions is shown in Figure 1. The differences with the present samples are that the encapsulation material was a highly filled, discontinuously reinforced aluminum alloy metal matrix composite. A comparison of selected properties between the Ti-6Al-4V and the DRA MMC material are shown in Table 1.
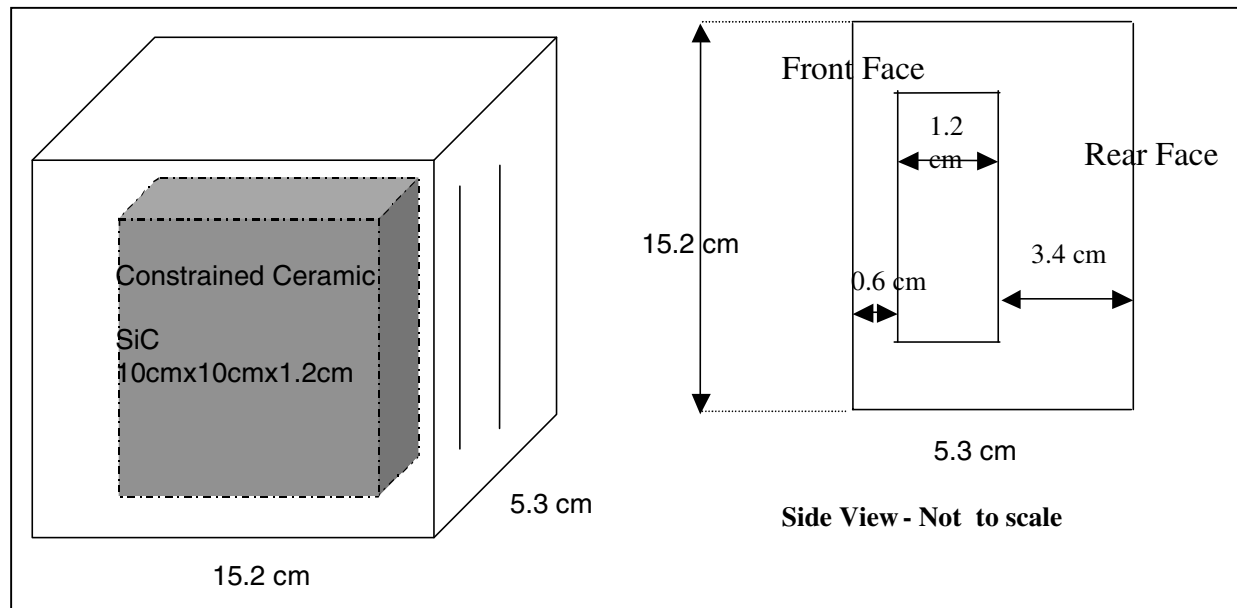
Figure 1. Encapsulated Ceramic / DRA Sample Configuration used for both the Pressure Infiltrated and the Pressureless Infiltration Casting processes.

Table 1. Comparison of Selected Properties of Materials Utilized in Encapsulated Samples			
	SiC Ceramic Tile	**356/SiC/60p-F MMC**	**Ti-6AL-4V**
Density	3.1 g/cc	2.9 g/cc	4.4 g/cc
Elastic Modulus	400 GPa	195 GPa	110 GPa
Coefficient of Thermal Expansion	4.4 /ºC	6.5 - 7.0 /ºC	9.3 /ºC
Yield Strength	(550) MPa	350 MPa	825 MPa
Est. Areal Density		24.6 psf	36.6 psf

2.2 Sample Preparation

The SiC tile material was provided by Horwath and was identified as being from the same lot of material from Cercom as used by Bruchey & Horwath [2] in their Titanium encapsulated targets. No further information is available at this time on the SiC tiles.

■   Pressure Infiltration Casting Process – The SiC tile was pre-positioned vertically and off center in the sample thickness direction in a graphite mold. Fine SiC particulate reinforcement, nominally 12 microns in size, was packed around the SiC tile. A vacuum was drawn and then the preheated mold was pressure infiltrated with molten aluminum 356 casting alloy. Further details of the fabrication casting process are commercially proprietary with the supplier. These samples were labeled MMC-01, MMC-02 and MMC-03, with front and back faces identified from the casting supplier. Later arbitrary markings of top, bottom, right and left side were made at ARL.

■   Pressureless Metal Infiltration Process – A fourth encapsulated sample was fabricated by a different supplier using the Pressureless Metal Infiltration Casting Process. In this process, a bed of SiC particulate is poured into a perforated mold, the SiC tile is placed on this loose particulate surface and additional SiC particulate is poured on top covering the tile. This assemblage is then place on top of an aluminum alloy plate and the entire system is heated in a furnace where the molten aluminum flows through the mold perforations and diffuses throughout the SiC perform via capillary action. After the infiltration was completed, the sample, identified as MMC-04, was very slowly cooled to room temperature. The front face of this sample was similarly identified by the supplier.

2. 3 X-ray Tomographic Inspection

2.3.1   Equipment – The samples were inspected using a customized ACTIS 600/420 computed tomography system designed and constructed by Bio-Imaging Research, Inc., and installed at the U.S. Army Research Laboratory at Aberdeen Proving Ground (APG), Maryland. The system has a 420 keV x-ray tube with two focal spot sizes and a 160 keV microfocus x-ray tube with four focal spot sizes, the smallest being 10 microns. It has a linear detector array (LDA) and an image intensifier with a zoom lens and a charged-coupled device (CCD) camera. Computed tomography scanning can be done using the LDA or the image intensifier (II). The system can scan in rotate-only (RO) and offset-RO mode using the LDA or the II as shown in Figure 2, and in translate-rotate (TR) mode using the LDA. It can also perform digital radiography (DR) scans using the LDA or II as shown in Figure 3.
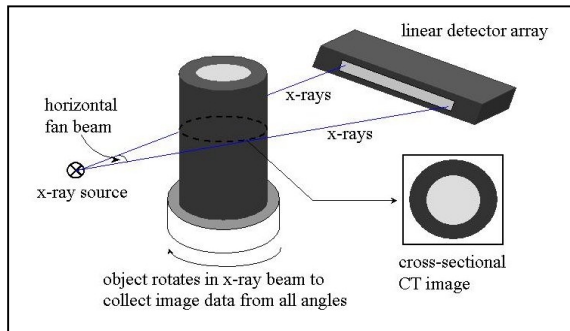
Figure 2. Schematic of the Rotate-Only (RO) Computed Tomography Scan
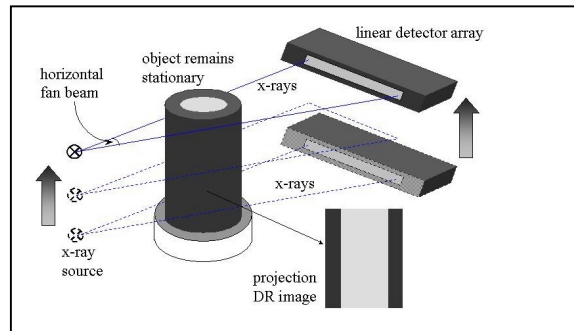
Figure 3. Schematic of the Digital Radiography Technique

2.3.2   NDT X-ray Procedure – Each sample was scanned perpendicular to their front and back face in TR mode from a height of approximately 22 mm to a height of approximately 122 mm. The cross-sectional image plane was parallel to the two inch (50.8 mm) through thickness direction. In TR mode the object being scanned is translated through the fan beam between finite rotations of the turntable. The source-to-object distance (SOD) in the direction of the source-to-image distance (SID) does not change. Rotation of the turntable occurs after each translation is finished. The TR scan data is reorganized into a set of equivalent RO views for the reconstruction process. The SOD and SID were 662.75 mm and 930.00 mm, respectively. The slice thickness and increment were 1.00 mm, resulting in contiguous scans. Each slice was reconstructed to a 1024 by 1024 image matrix. Scan time was about 32 minutes per slice with 100 slices required to scan the 100 mm distance. The scan configuration used the 420 keV x-ray tube with the linear detector array (LDA). The tube energy and current used were 350 keV and 2.5 mA for samples MMC-01 and MMC-02 and 370 keV and 2.25 mA for sample MMC-03, and the focal spot was 0.8 mm for each sample.

3.   RESULTS

3.1 Visual Inspection – Digital macro-photographs were taken of each sample as received from the casting supplier. Photomacrographs of the front surface of each sample are shown in Figure 4. Indications of cracking are visible on the front surface of all three pressure infiltrated samples as shown in in Figure 4 (a),(b) and (c). No such indications were observed on the front surface of the pressure-less infitration sample in Figure 4 (d).

Figure 4 (a). Front surface of sample MMC-01 with cracking visible.

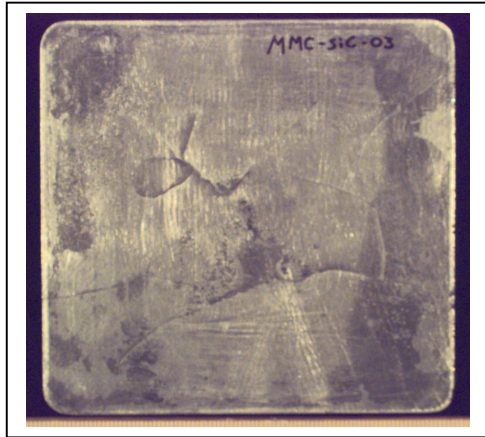Figure 4 (b). Front surface of sample MMC-02 with cracking visible.

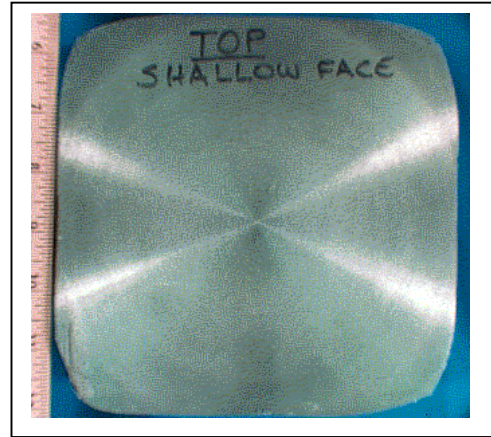Figure 4 (c). Front surface of sample MMC-03 with cracking visible.

Figure 4 (d). Front surface of sample MMC-04 with no surface cracking observed.

3.2 Digital Radiography– A digital radiograph, DR, in the through thickness direction was taken of each sample. These are shown in Figure 5 (a), (b), and (c) for samples MMC-01, MMC-02, and MMC-03, respectively. The purely vertical streaking in each DR is an image artifact and does not correspond to material or structural differences in the samples. A substantial amount of cracking is evident in each of the pressure infiltrated samples, Figures 5(a), (b) and (c). Also, the internal SiC tile, which appears lighter than the surrounding matrix, is not centered top-to-bottom, nor centered left-to-right, tilted to some degree, or some combination of these translational conditions. Note that it is not evident from the DR whether such cracking extends from the MMC into the SiC tile material or remains in the projected MMC plane in front of and/or behind the tile. Similarly, no tile displacement toward or away from the front face of the sample is discernable in the DR. Neither cracking nor SiC tile displacement was observed in the conventional radiograph of the pressureless infiltration sample MMC-04.
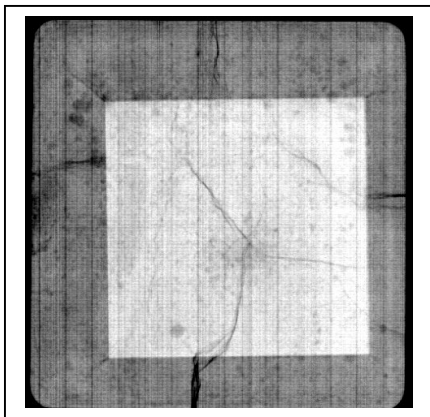

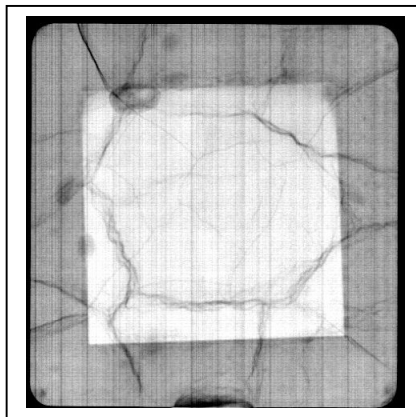Figure 5(a). Digital Radiograph of Sample MMC -01.

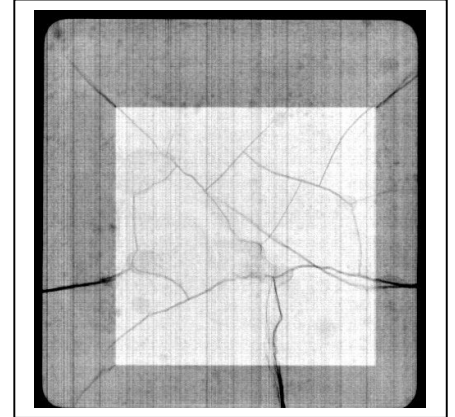Figure 5(b). Digital Radiograph of Sample MMC-02.

Figure 5(c). Digital Radiograph of Sample MMC-03.

**3.3 X-ray Computed Tomography, CT, Scans of Sample MMC-01, -02 and -03**

Figure 6 is a representative series of four CT images in which the front face of the sample MMC-01 is at the bottom of the image. Cracking in both the DRA material and the SiC tile is evident in these cross sectional reconstructed views. This cracking appears predominantly initiating on the front face and, in Figure 6 (c), continues directly into the SiC tile. The tile has moved during the pressure infiltration process and is now only about 2mm from the front face of the sample. Porosity up to about 3 mm in diameter is also observed in the DRA material in these cross sectional CT views
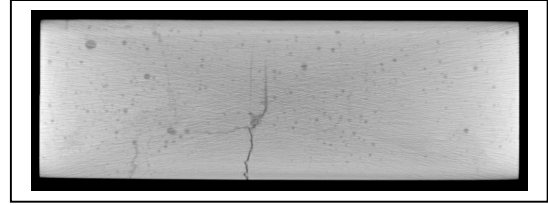.
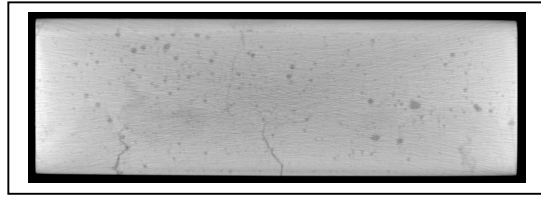
(a) Above top of SiC tile Sample MMC-01
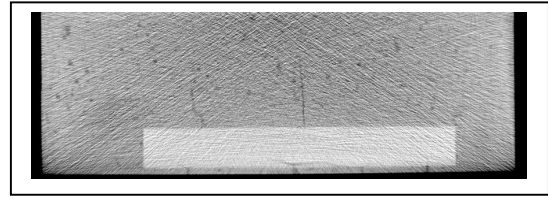
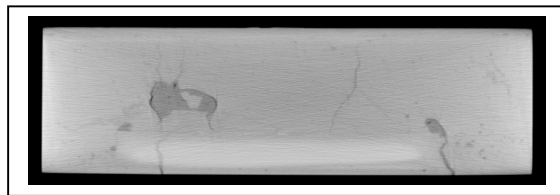(b) Near lower quarter of tile (48 mm)
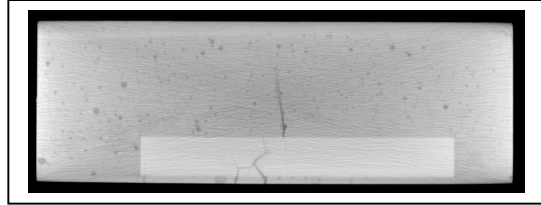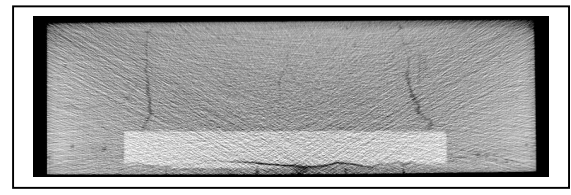

(c) Near bottom of tile

(d) Near bottom of sample MMC-01

Figure 6 (a) to (d) showing x-ray CT scans across various cross sectional positions of sample MMC-01. Note the cracking in both the DRA and the SiC tile materials and the forward translation of tile.
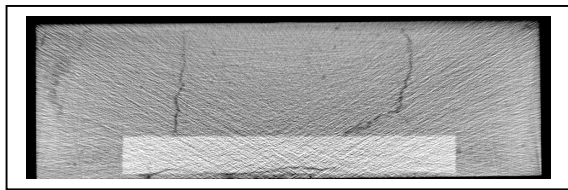
Figure 7 is a similar series of CT images for sample MMC-02. Large inclusions and extensive cracking in the DRA material is evident, as well as cracking in the SiC tile. There is a relatively thin void area to the left of the large inclusion. Also, the corners and some of the edges of the tile in Figure 7 (a) are missing. Again, the tile is within only a few millimeters of the front face of the sample demonstrating the plate was displaced during the DRA pressure infiltration casting process. Note that extensive lateral cracking has occurred along the front face of the SiC tile as shown in Figures 7 (b) and (c).
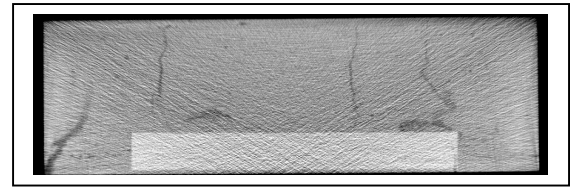

(a) Neat top of tile in Sample MMC-02

(b) Upper tile quarter section (105 mm)

(c) Lower quarter tile section (53mm)

(d) Near bottom of Tile in Sample MMC-02

Figure 7 (a) to (d) showing x-ray CT scans across various cross sectional positions of sample MMC-02. Note the large inclusions and extensive cracking in the DRA and both transverse and lateral cracks in the SiC tile material.

Figure 8 is the series of CT images for sample MMC-03. Again, cracking in both the DRA material and the SiC tile is evident in this sample as well. Prominent cracks originating on the front face are seen to bridge the DRA material perpendicular to the tile, and turn laterally once into the SiC tile as shown in Figures 8 (b) and (c). The tile is not horizontally centered and is tilted with respect to the front face of the sample. Lastly, the tile is closer from the front face near the top of the sample than it is near the bottom of the sample, indicating a vertical tilting as well.

(a) Near top of tile in Sample MMC-03

(b) Upper quarter section of tile (94mm)

(c) Lower quarter section of tile (44mm)

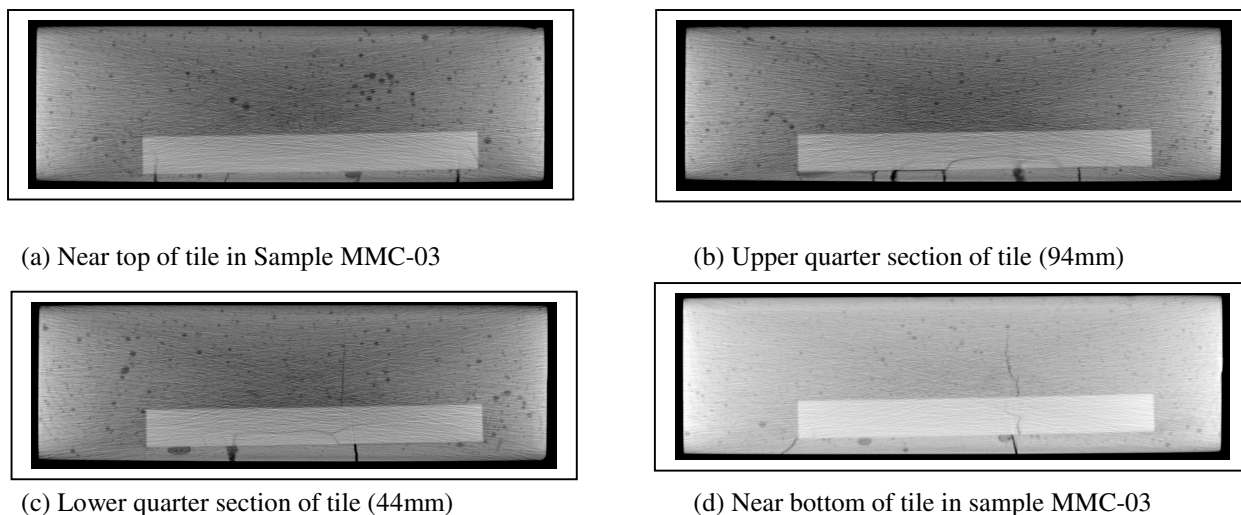(d) Near bottom of tile in sample MMC-03

Figure 8 (a) to (d) showing x-ray CT scans across various cross sectional positions of sample MMC-03. Note the prominent cracking in front face of the DRA and turning transversely in the SiC tile.

4.   CONCLUSIONS AND RECOMMENDATIONS

• X-ray computed tomography has been demonstrated as an acceptable nondestructive technique for the purpose desired herein. First, a baseline of pre-existing damage and SiC tile displacement in both the DRA encapsulation material and in SiC tile has been observed and recorded in all three of the samples fabricated by the Pressure Infiltraion Casting process. A more recent initial sample fabricated by the Pressureless Infiltration Casting process resulted in the absence of such cracking and no detectable tile displacement in the as-fabricated condition.

• Substantial pre-existing flaws including cracking in both the DRA encapsulating material and in the monolithic SiC ceramic tile were observed in the samples cast with the Pressure Infiltration technique. Size, location, orientation, and shape of flaws were observed and recorded to establish a "pre-impact" baseline for planned subsequent examination following ballistic impact. A significant forward displacement and tilting of the SiC tile was detected resulting from the Pressure Infiltration Casting process where inadequate tile restraint was incorporated in the mold/preform. This displacement of the monolithic SiC tile is significant both in the through thickness and in the orthogonal planar directions. Such cracking and tile displacement are undesirable and were clearly detected and adequately characterized by the nondestructive x-ray tomography method so as to justify the postponement of the planned subsequent ballistic testing of these samples.

• It is desirable to extend this characterization technique to the HIP Ti-6Al-4V / SiC samples of Bruchey and Horwath and other armor target configurations in the future. However, the existing 420kv CT facility presently available to the authors is unable to penetrate the higher density Titanium alloy samples of comparable size.

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